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... for a brighter future

Beam Physics Studies at the AWA facility

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DOE Review

April 26, 2007

U.S. Department of Energy

UChicago Argonne LLC

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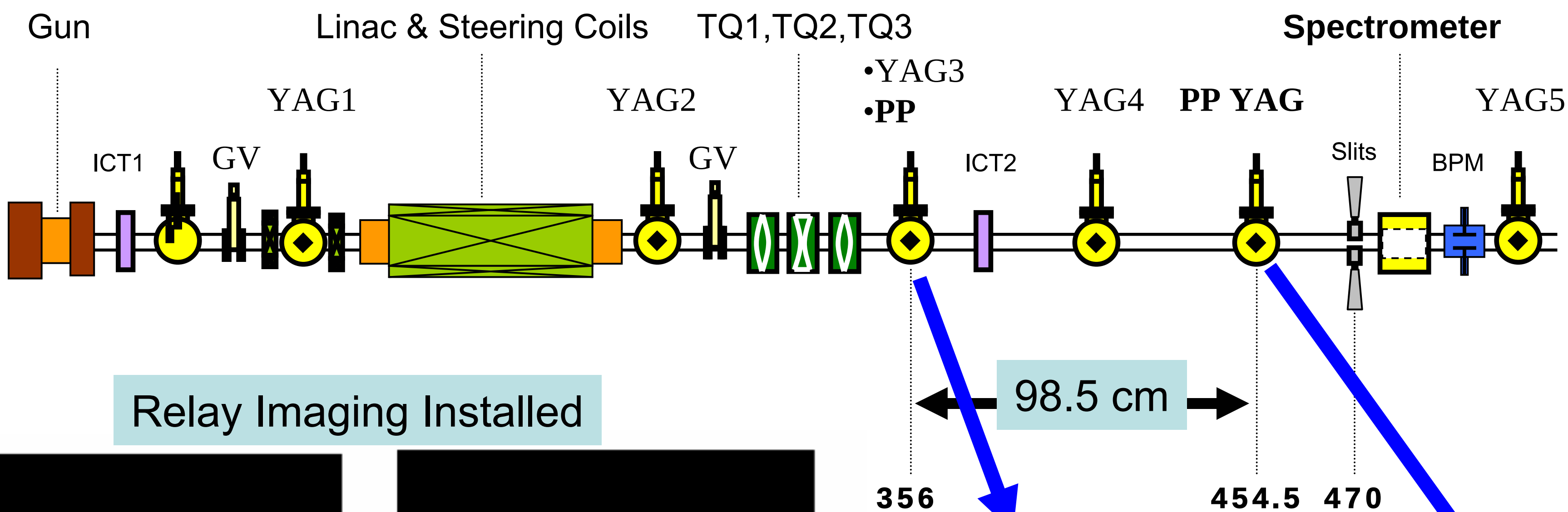
Key to success
Knowledge and Control of Beam Physics

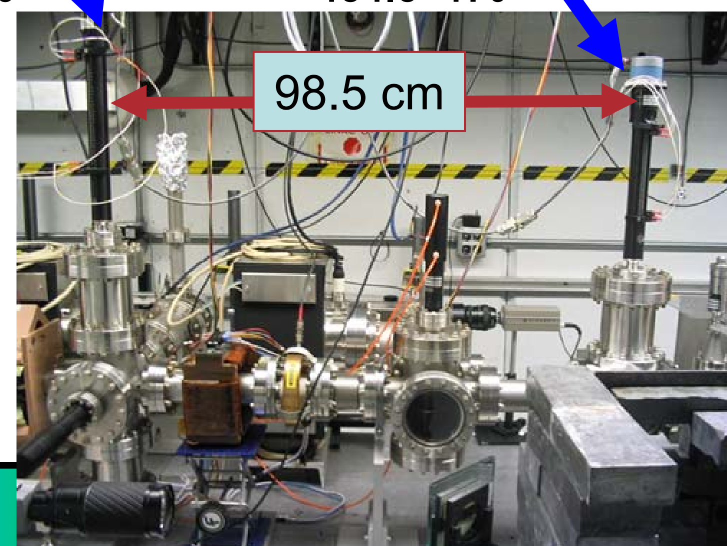
- **Fundamental Beam Physics**
  – Beam generation, emittance preservation, characterization (diagnostics), BBU control, phase space manipulation
- **High-current beam production**
  – Beam-driven wakefield acceleration & RF generation schemes.

- **06-07 Progress and Future Directions →**
  – Pepper-pot Transverse Phase space measurements
  – Aerogel-based Bunch Length Measurements
  – Electro-Optic Sampling
  – ODR-DFR transverse emittance measurements
  – Space-Charge Mixing
  – Emittance Exchange

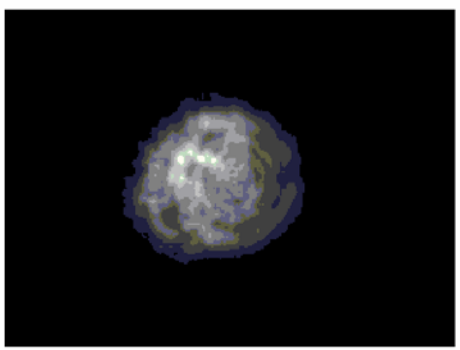
1.3 GHz RF Photoinjector Phase Space Measurements

Accurate emittance measurements yield realistic input data for realistic simulations. This will help to understand losses and eventually increase the beam current and brilliance.

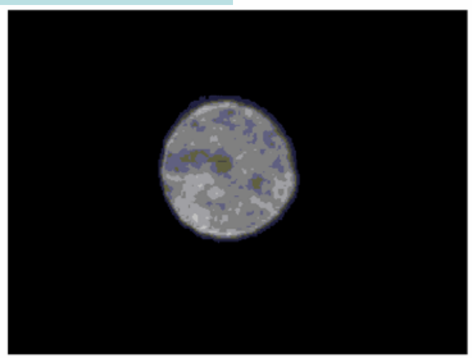




Relay Imaging Installed



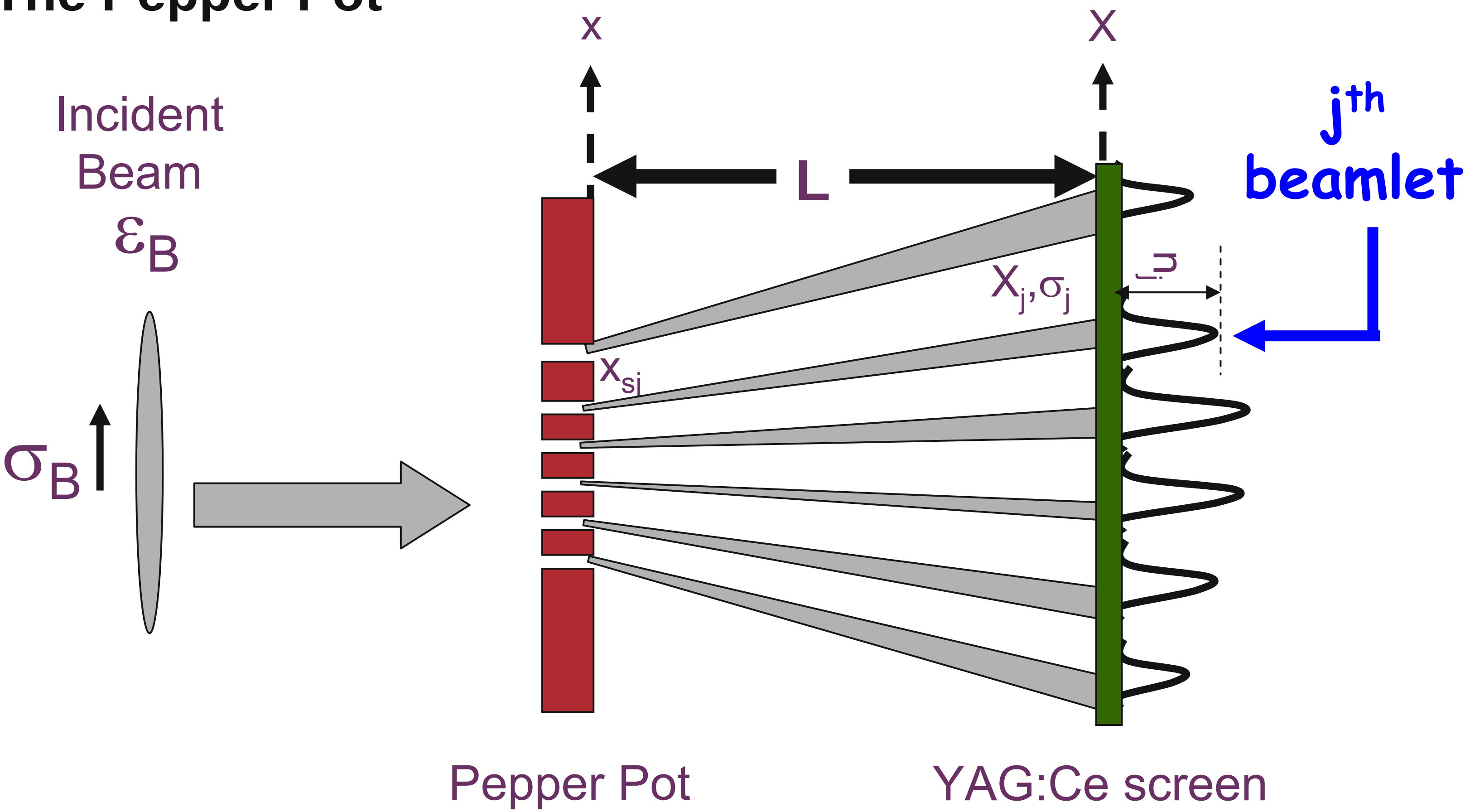
Diffraction Rings Present
(December 2005)



Using Relay Imaging
(August 2006)

Phase Space Measurement of Transverse Phase Space

The Pepper Pot

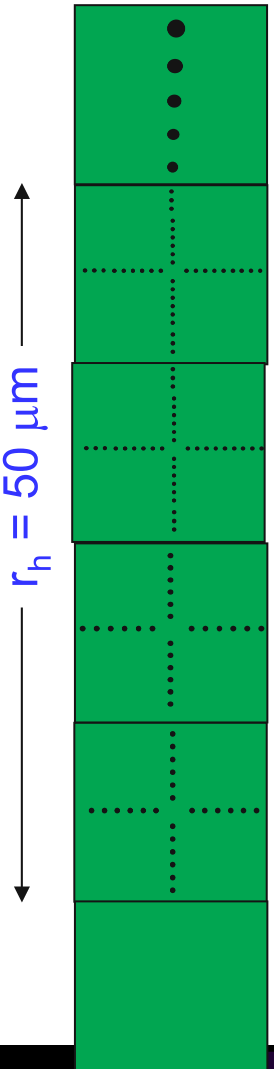


$$\varepsilon_{rms}^2 \approx \frac{1}{N^2}\left\{\left[\sum_{j=1}^{p} n_j\left(x_{sj}-\overline{x}\right)^2\right]\left[\sum_{j=1}^{p}\left[n_j\left(\frac{\sigma_j}{L}\right)^2+n_j\left(\overline{x}_j'-\overline{x}'\right)^2\right]\right]-\left[\sum_{j=1}^{p} n_j x_{sj}\overline{x}_j'-N\overline{x}\overline{x}'\right]^2\right\}$$

Phase Space Measurements …

Experimental Setup

Pepper Pot Actuator (wide dynamic range)



r=12.5 – 200 μm

0.7 mm spacing

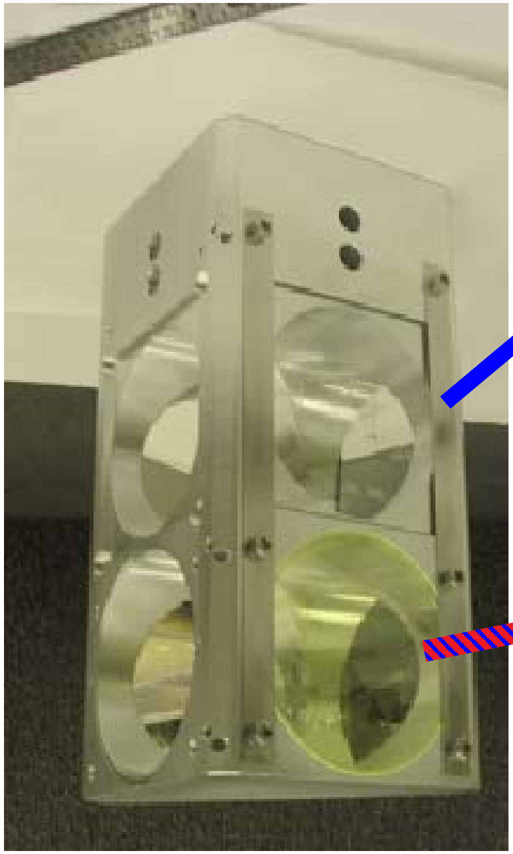
0.8 mm spacing

0.9 mm spacing

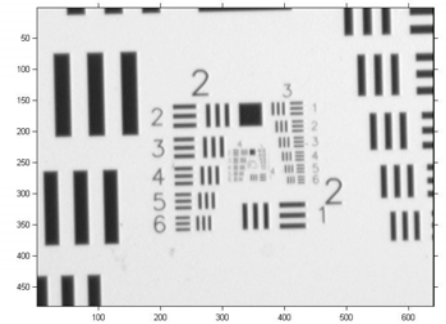
1mm spacing

blank

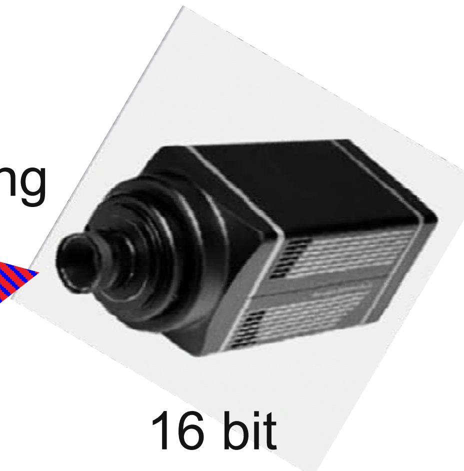
High Resolution YAG:Ce th.=100μm; normal incidence



USAF 1951 Res. Target



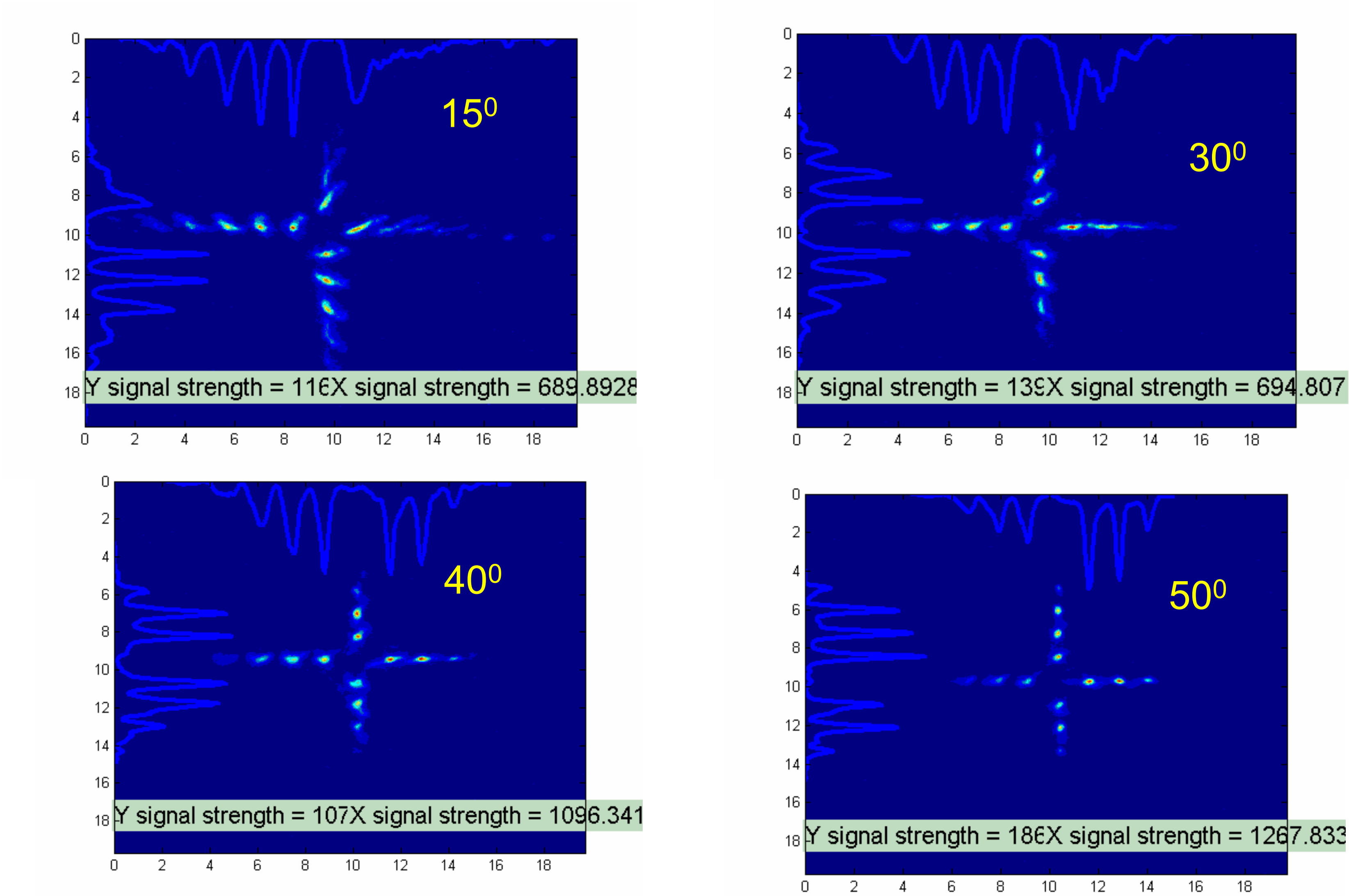
1:1 imaging



16 bit ICCD camera (50 nsec gate)

Phase Space Measurements …

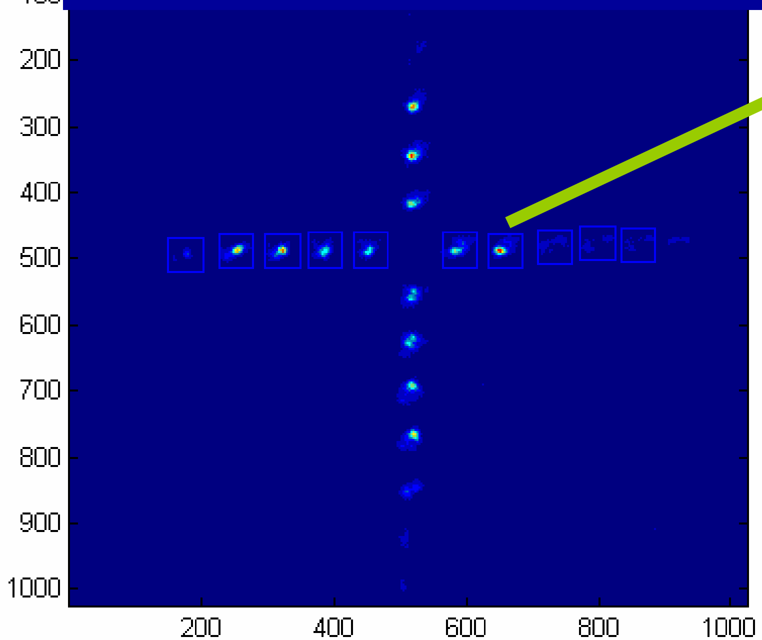
Parametric Study: ε vs. gun(ϕ)



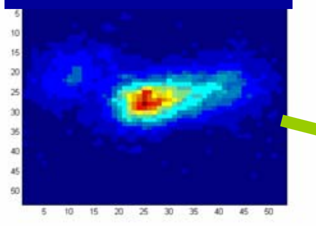
Phase Space Measurements …
Image Analysis

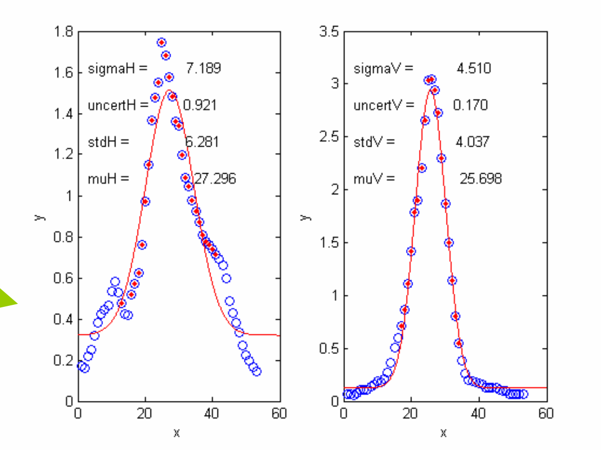
$$\varepsilon_{rms}^2 = \langle x^2 \rangle \langle x'^2 \rangle - \langle x'x \rangle^2$$

Pepper Pot Beamlets on screen



j^{th} beamlet





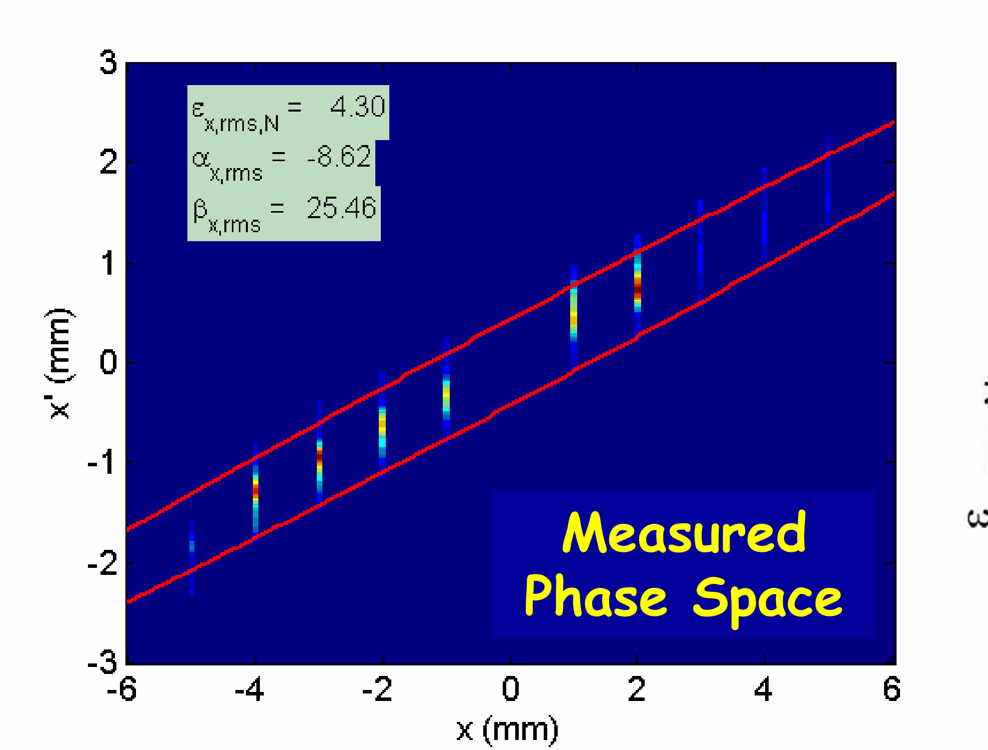
Calculate rms properties of projections

$$\sigma_j, n_j, \overline{X}_j \; \{ j = 1,2,\ldots p \}$$

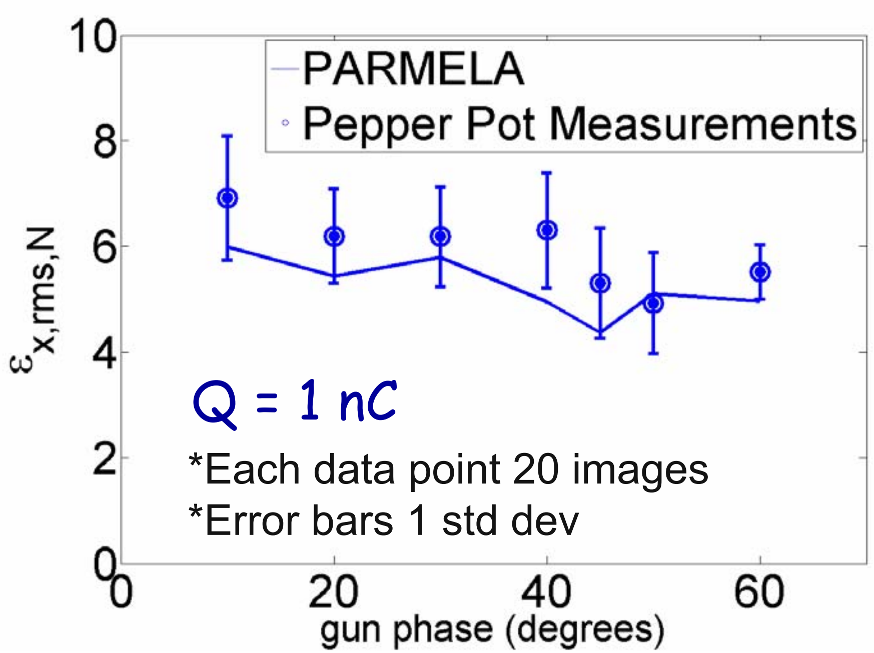
$$\varepsilon_{rms}^2 \approx \frac{1}{N^2} \left\{ \left[\sum_{j=1}^{p} n_j \left(x_{sj} - \overline{x} \right)^2 \right] \left[\sum_{j=1}^{p} \left[n_j \left(\frac{\sigma_j}{L} \right)^2 + n_j \left(\overline{x'_j} - \overline{x}' \right)^2 \right] \right] - \left[\sum_{j=1}^{p} n_j x_{sj} \overline{x'_j} - N \overline{x} \overline{x}' \right]^2 \right\}$$

Phase Space Measurements …

Comparison of PARMELA and measured phase space



Good agreement between measurement and PARMELA

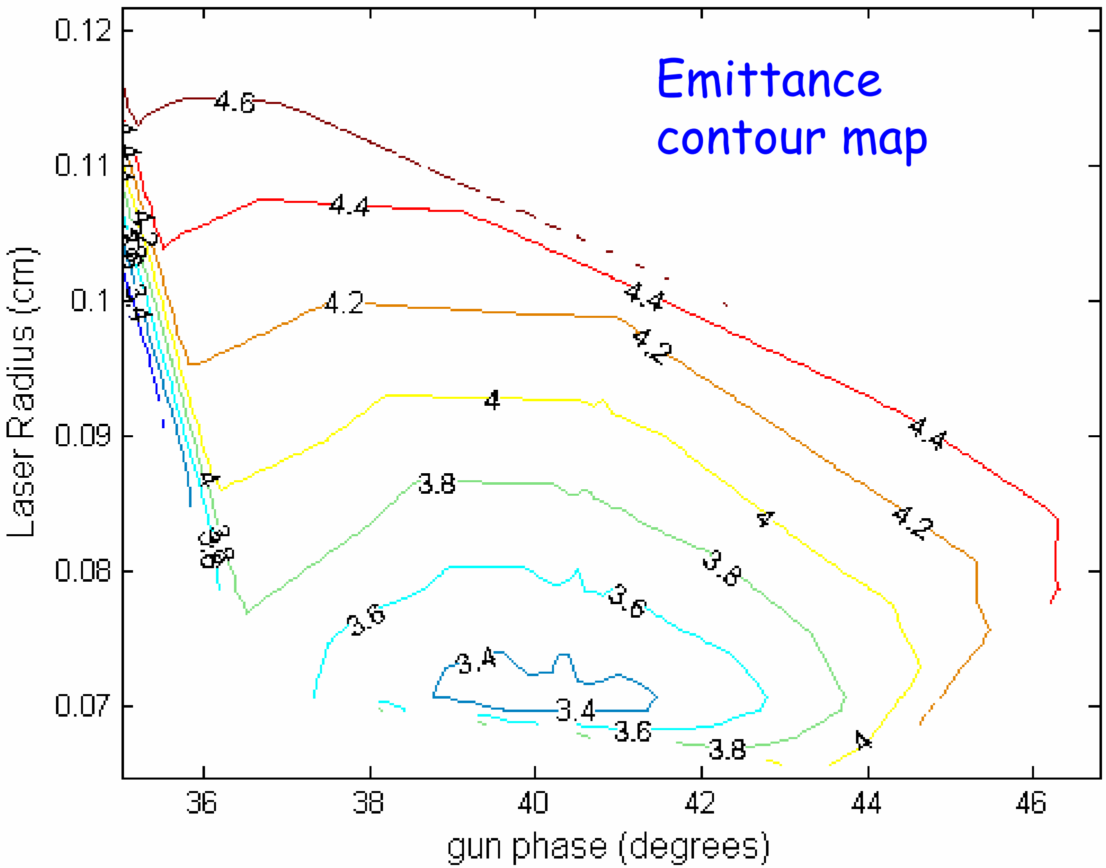


Twiss Parameters are retrieved from each pepper pot beamlet image.

High Brightness Photoinjector Operation

Future Directions: path to brighter beam

- Recent Parmela simulations (coupled to Matlab's Optimization Toolbox) show path to higher brightness →
  - smaller laser radius
  - higher solenoid fields
  - longer laser pulse

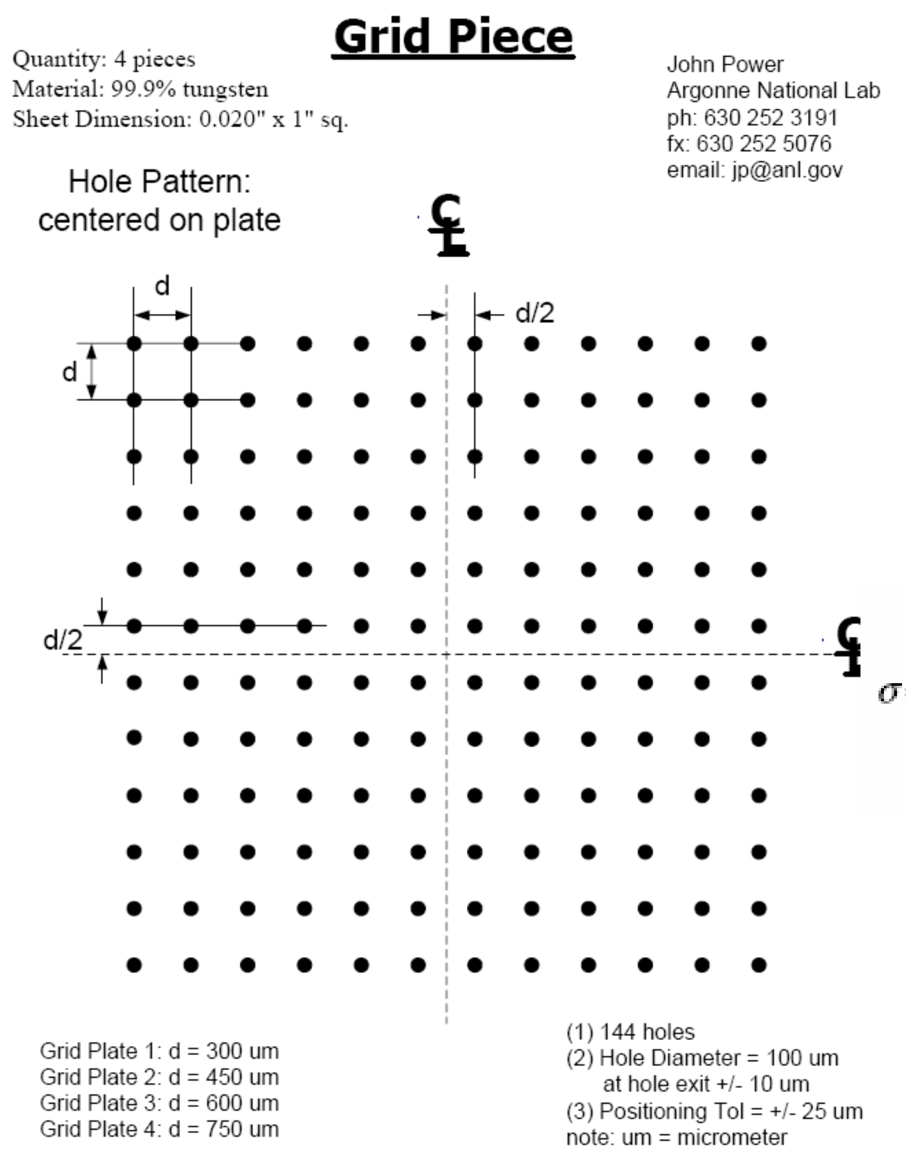


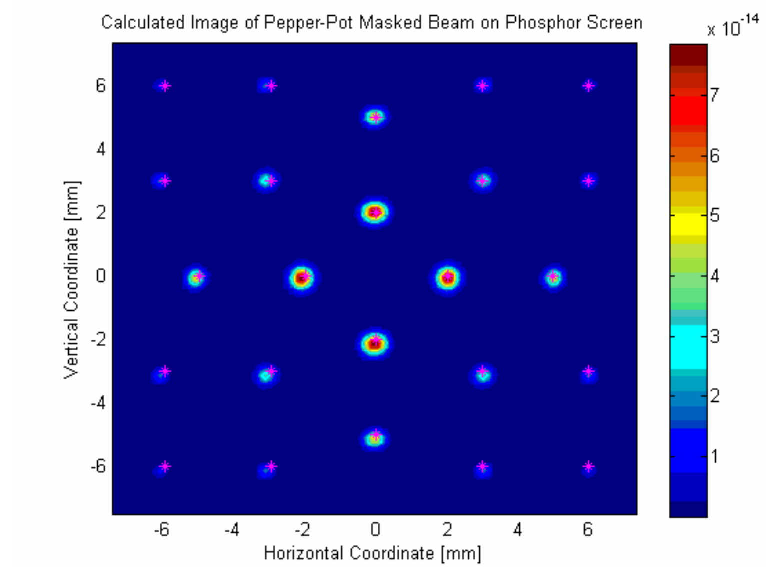
1. Can reach 3 μm easily

2. Approach to 1 μm needs a reconfiguration of the AWA laser to lengthen laser pulse length

High Brightness Photoinjector Operation

Future Directions: 4D emittance measurements



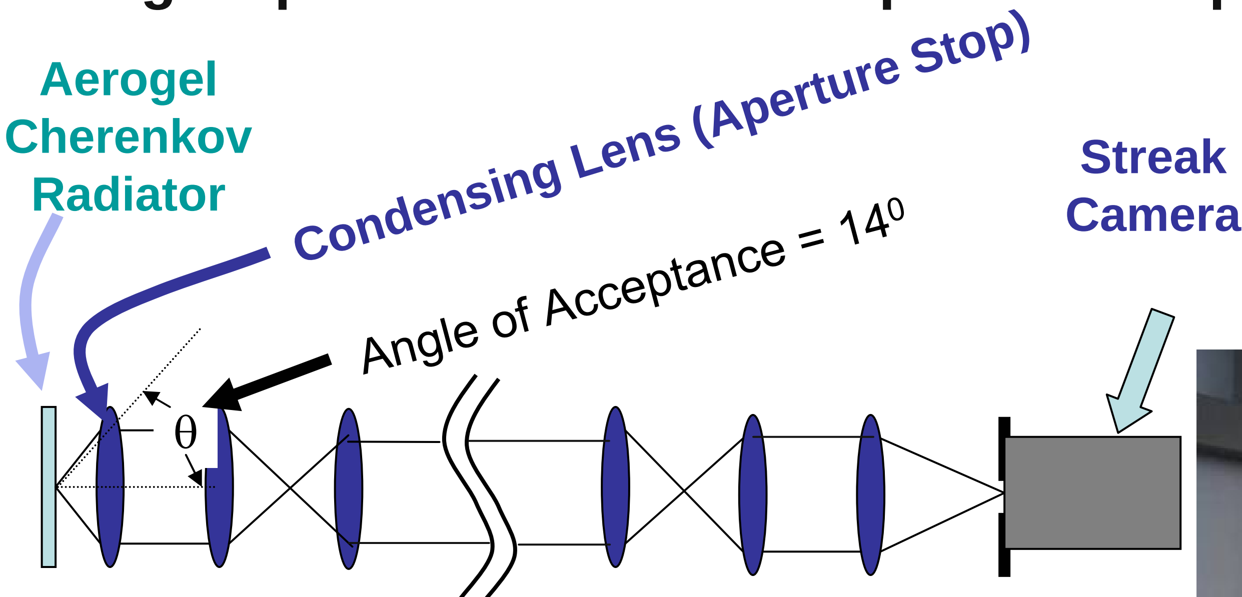


$$\sigma = \begin{pmatrix} \langle x^2 \rangle & \langle xx' \rangle & \langle xy \rangle & \langle xy' \rangle \\ \langle xx' \rangle & \langle x'^2 \rangle & \langle x'y \rangle & \langle x'y' \rangle \\ \langle xy \rangle & \langle x'y \rangle & \langle y^2 \rangle & \langle yy' \rangle \\ \langle xy' \rangle & \langle x'y' \rangle & \langle yy' \rangle & \langle y'^2 \rangle \end{pmatrix}, \quad \varepsilon_{4D} = \sqrt{\det(\Sigma)}$$

- Projected 2D emittance
- Measurement of x-y coupling

Bunch Length Measurements at the AWA

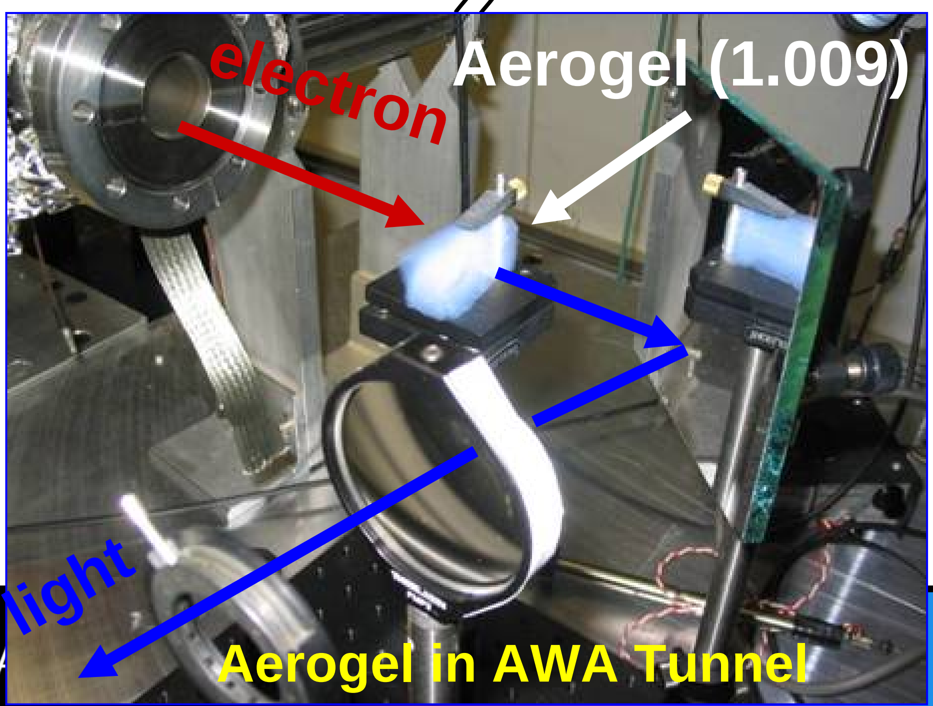
A High-Aperture Achromatic Optical Transport Line



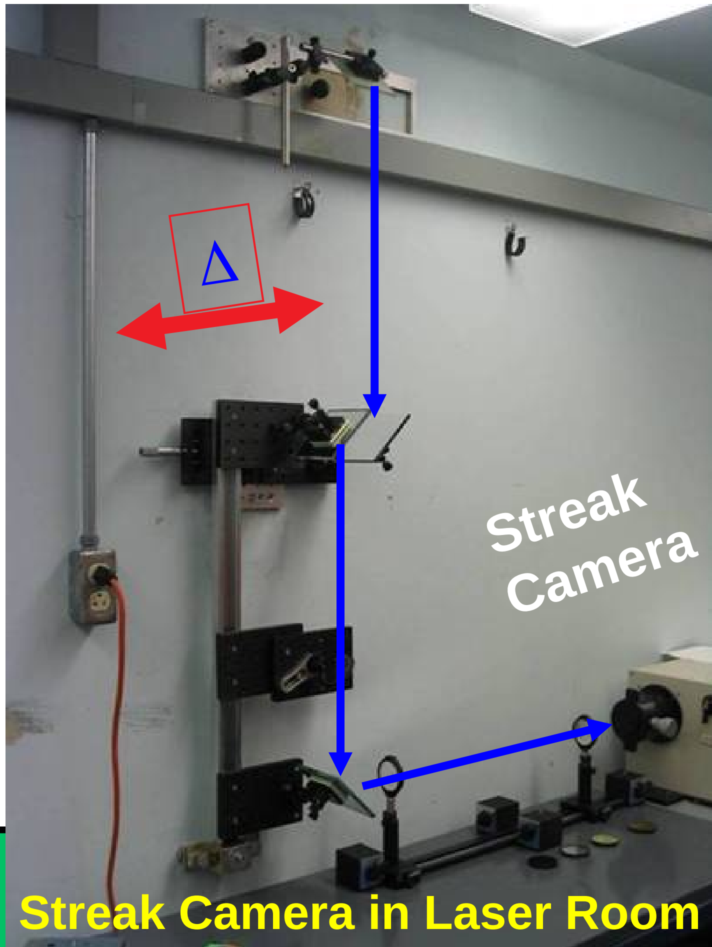
Design Goals

→max light collection

→min dispersion



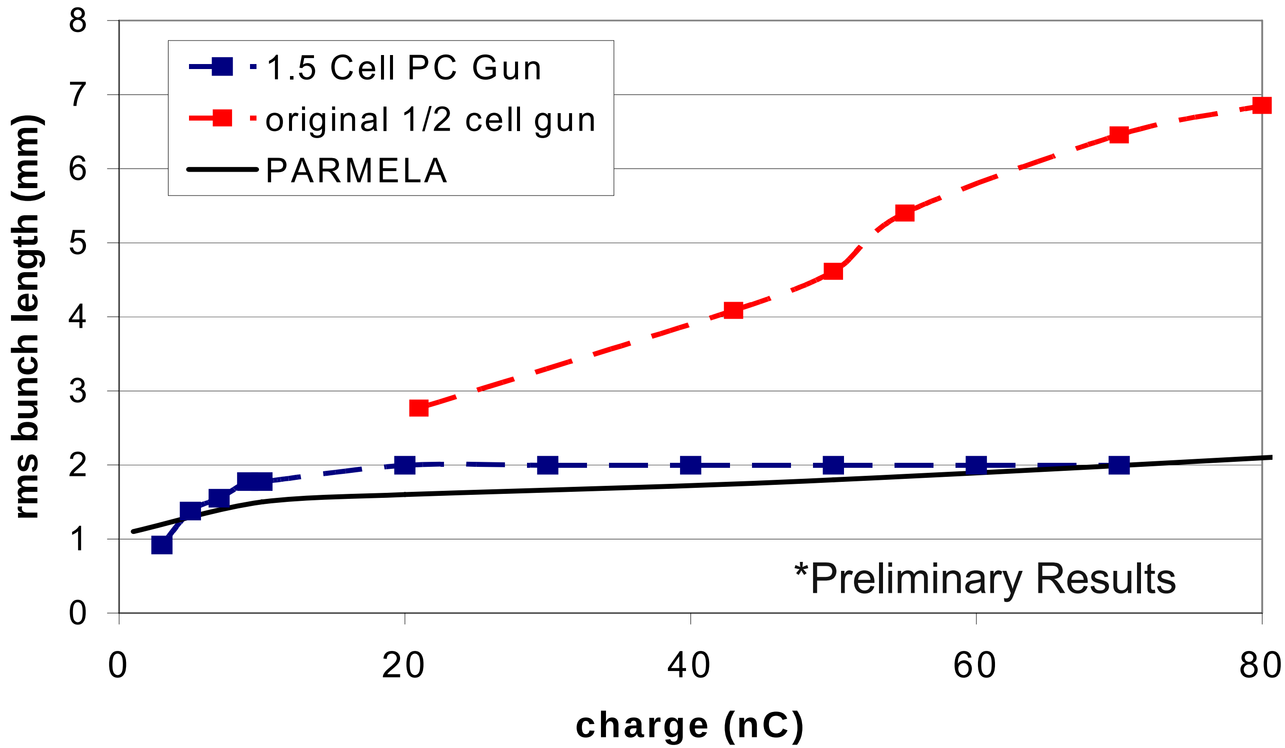
Aerogel in AWA Tunnel



Streak Camera in Laser Room

Bunch Length Measurements

Experimental Results*

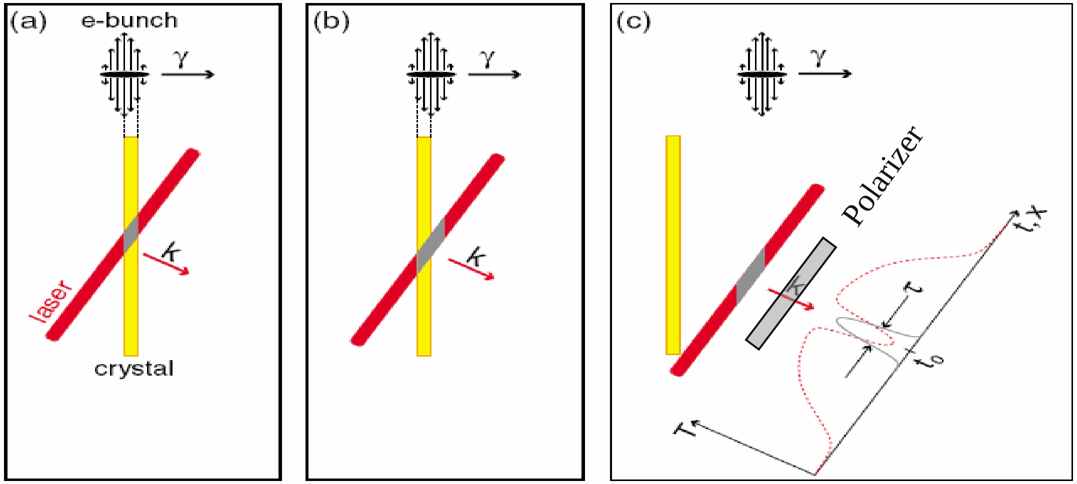


- Bunch length is approximately inline with simulations
- Needed 10 nm BP filter → Achromatic doublets were not sufficient to control dispersion, all reflective system under consideration

Advanced Diagnostic Development

Electro Optic Sampling Experiment

- **Goal:**
  - High Resolution of EOS allows for fundamental physics study → the longitudinal current density along the length of the e^- beam
- **Collaborators:**
  - T. Maxwell (NIU Graduate Student); J. Ruan, V. Scarpine, R. Thurman-Keup (FNAL); Y. Li (APS)
- **Concept: Spatial Decoding**



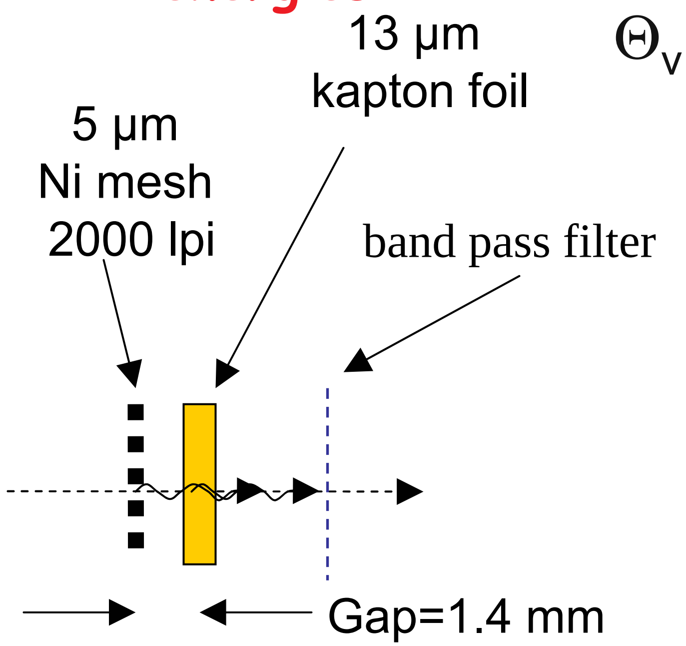
- The femtosecond laser pulse is focused as a line image to the crystal and passes the crystal at an angle
- The bunch length is transferred to the spatial structure of the laser

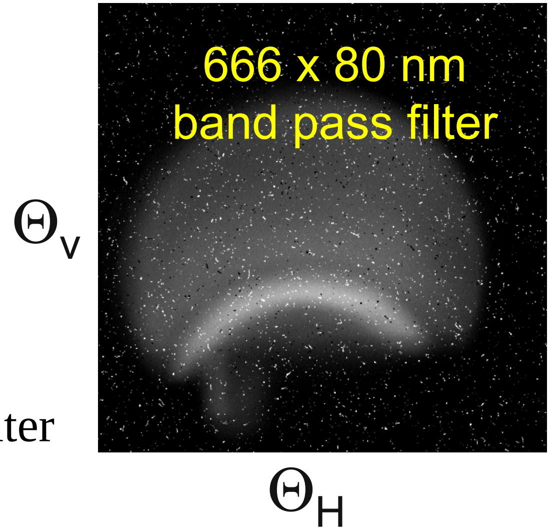
- **Current:** Laser-based THz Generation of a 'simulated' e^- beam
- **Next:** Measure current density of AWA e^- beam

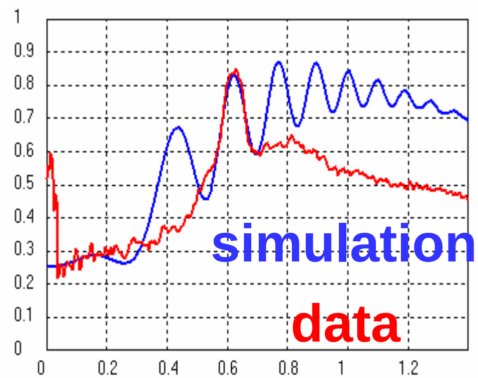
Advanced Diagnostic Development

Optical Diffraction Radiation – Dielectric Foil Radiation

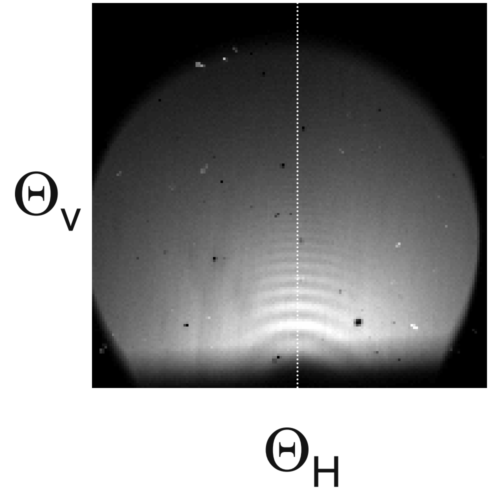
Applying the OTR-based diagnostic to low energies

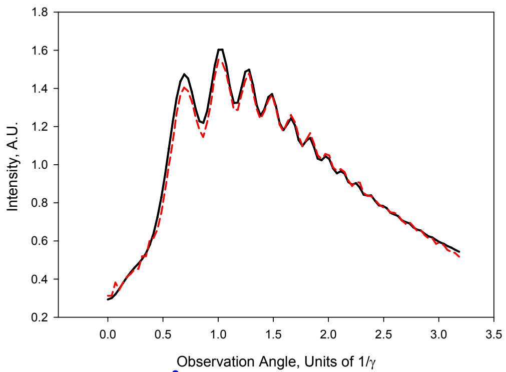






first experiment:
missing fringes due to misalignment





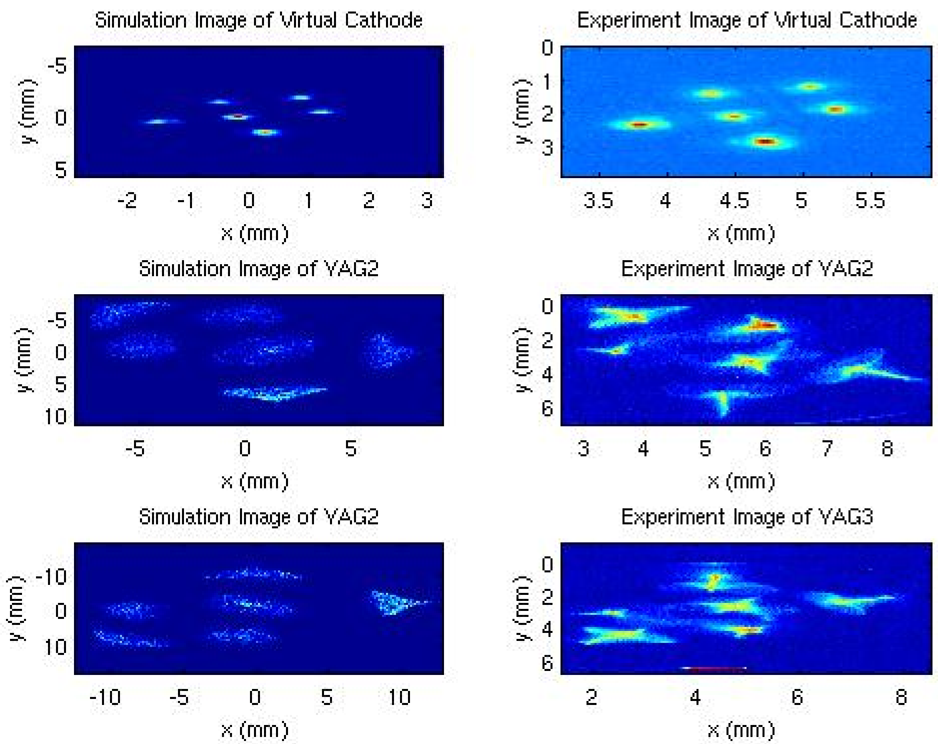
second experiment:
Observed ODR-DFR Interference at E= 14.2 MeV when beam divergence lowered by vertically expanding beam

third experiment:
→Waited until Pepper Pot Measurement was completed
→Planned for May 07

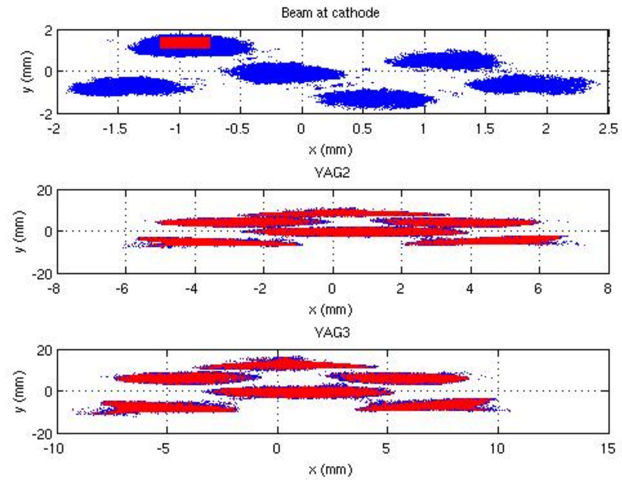
Fundamental Beam Physics

Space-charge studies

- Benchmarking of space charge algorithms
- Simulations with IMPACT-T & NIU's wavelet-based algorithm
- M. Rihaoui (NIU Master's Thesis)



Space Charge Mixing



Quantify: How well does the algorithm reproduce the features observed in the AWA experiment?

Phase Space Manipulation

Emittance Exchange (E-X) Experiment at the AWA facility

<-- Concept -->

exchange the longitudinal and transverse emittances

Collaborators/Contributors:

APS: K.-J. Kim, Y.-e. Sun, K. Harkay

NIU: P. Piot; M. Rihaoui

AWA: S. Antipov, M. Conde, W. Gai, C. Jing, W. Liu, **J. G. Power**

… a newly emerging effort

… LDRD & NIU funding

The Argonne Emittance Exchange Webpage:
http://aps.anl.gov/Accelerator_Systems_Division/Accelerator_Physics/emitExchange/index.htm

What is Emittance Exchange …

and why should we do it?

1. The reason we (HEP) care: May eliminate the need for the electron damping ring for the ILC
2. The reason our collaborators (APS/BES) care: Will improve the x-ray FEL performance
3. The reason we all care: State of the art in beam physics ☺

- ILC requirement:

  $\gamma(\varepsilon x,\ \varepsilon y,\ \varepsilon z) = (8,\ 0.02,\ 3000)\ \mu m$

  $\varepsilon 6D = \gamma\,(\varepsilon x^{*}\varepsilon y^{*}\varepsilon z)^{1/3} = 10\ \mu m$

- RF Photoinjector capability:

  $\gamma(\varepsilon x,\ \varepsilon y,\ \varepsilon z) = (5,\ 5,\ 8)\ \mu m$

  $\gamma\varepsilon 6D = \gamma\varepsilon x^{*}\varepsilon y^{*}\varepsilon z = 5\ \mu m$

round-to-flat-beam transformation

$$(5, 5, 8) \rightarrow (1250, 0.02, 8) \rightarrow (8, 0.02, 1250)$$

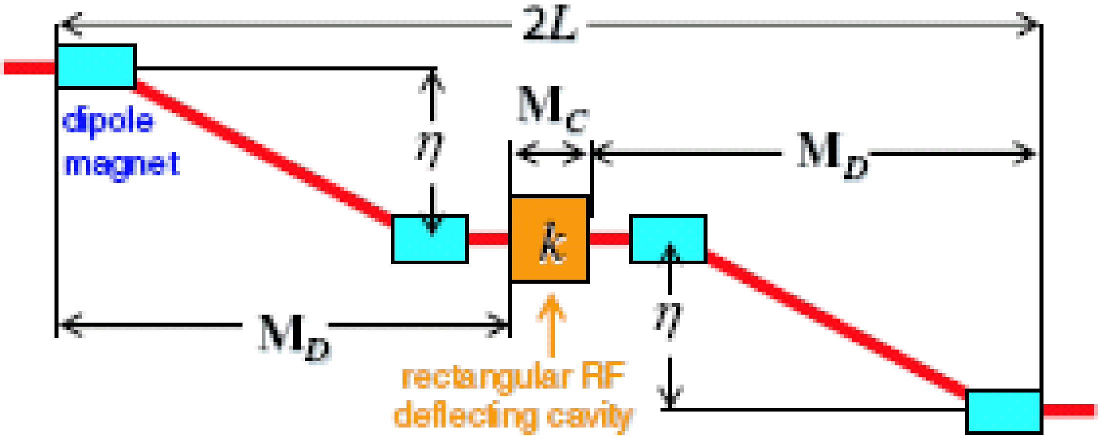
Longitudinal-transverse E-X

Exchanger beamline[1,2]

Can we design a beamline (transfer matrix M_{EX}) that will do the flip?

- Yes, at least in the thin-lens approximation → Double dog-leg

$$M_D(\eta,\xi,L)=\begin{bmatrix}1 & L & 0 & \eta\\ 0 & 1 & 0 & 0\\ 0 & \eta & 1 & \xi\\ 0 & 0 & 0 & 1\end{bmatrix}$$



$$M_C(k)=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & k & 0\\ 0 & 0 & 1 & 0\\ k & 0 & 0 & 1\end{bmatrix}$$

$$M_{EX}=M_D(\eta,\xi,L)M_C(k)M_D(\eta,\xi,L)$$

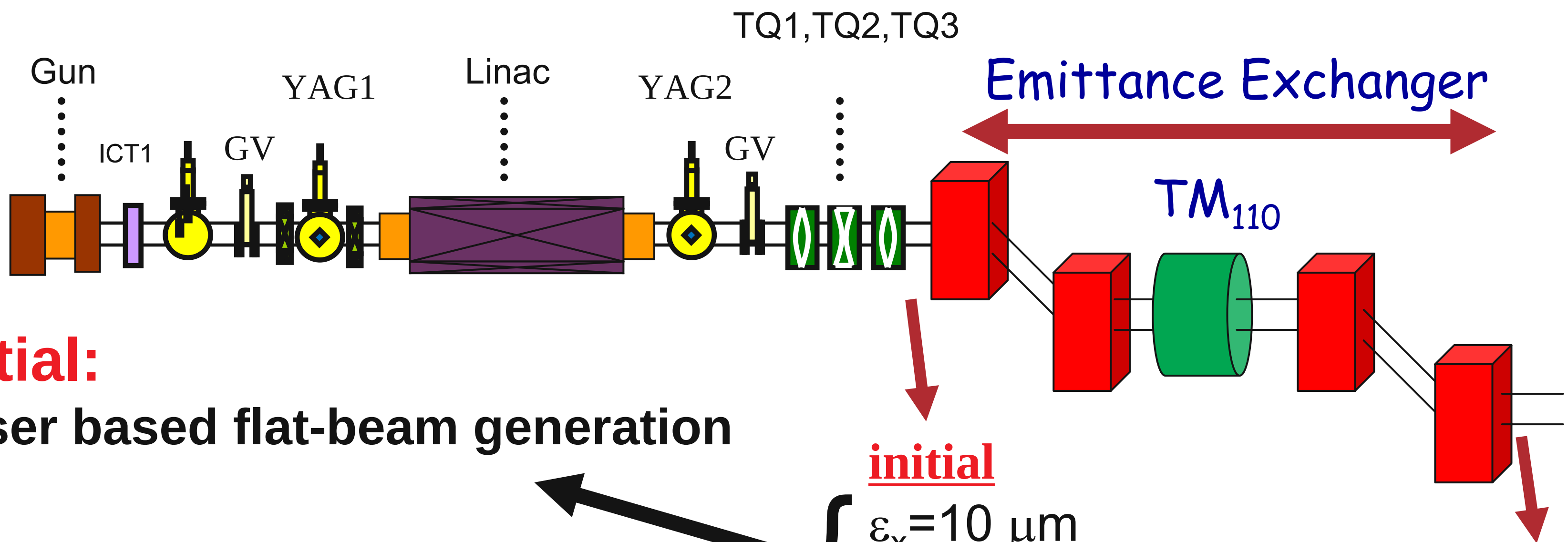
$$\boxed{M_{EX}=\begin{bmatrix}0 & 0 & kL & \eta+kL\xi\\ 0 & 0 & k & k\xi\\ k\xi & \eta+kL\xi & 0 & 0\\ k & kL & 0 & 0\end{bmatrix}}$$

Exchange Solution → $k^*\eta=1$

1. M. Cornacchia and P. Emma, Phys. Rev. ST Accel. Beams 5, 084001 (2002).
2. P. Emma, Z. Huang, K.-J. Kim and P. Piot, Phy. Rev. ST Accel. Beams 9, 100702, (2006).

E-X experiment at the AWA

Layout of beamline in the AWA Test Stand



Initial:

Laser based flat-beam generation

initial

ε_x=10 μm
ε_y=3 μm
ε_z= 3 μm

final

ε_x= 3 μm
ε_y=3 μm
ε_z= 10 μm

Future:

round-to-flat beam transformation

In the early stages of the experiment, but some progress …

- **Design deflecting cavity (AWA)**
- **Design ‘thin-lens’ beamline (APS/NIU)**
- **Design ‘thick-lens’ beamline (APS/NIU: GPT, Elegant)**
- **Simulate laser-based flat beam generation (NIU: Impact-T)**
- _
- Fabricate cavity (Tsinghua University)
- Experimentally verify flat-beam scheme
- Purchase/Install magnets, vacuum pumps, vacuum chamber
- Design and build TOF measurement system
- Design and build stripline BPMs
- Commission cavity
- Commission beamline
- Demonstrate Emittance Exchange
  - Measure Transfer Matrix
  - Measure 6D emittance before and after exchanger
- Ph.D. Thesis Topic for M. Rihaoui (NIU/AWA)
- _

Deflector Cavity Design

Required Cavity Kick Factor

- **Required kick from cavity :**
  - **Current AWA exchanger design has dispersion η=0.25 m at cavity**

recall → η ∗ T=1

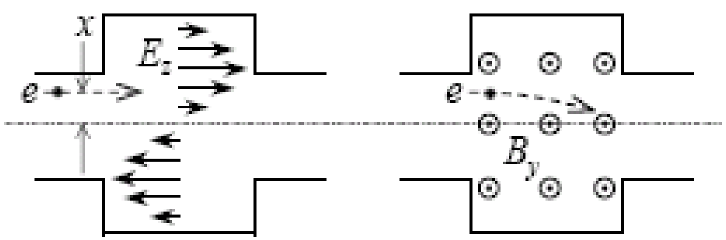
Required kick factor
T=4

- **Required field strength using TM_{110} pillbox**

$$E_z(r,\theta,z,t)=E_0J_1(kr)\cos(\theta)\cos(\omega t)$$ **→ near axis →** $$E_z(x,y,z,t)=E_0\frac{kx}{2}\cos(\omega t)$$

$$\delta=\frac{dW}{W_0}=\frac{1}{W_0}\int_0^d eE_z(x)dz$$

$$\delta=\left(\frac{E_0 d}{W_0/e}\frac{k}{2}\right)x$$



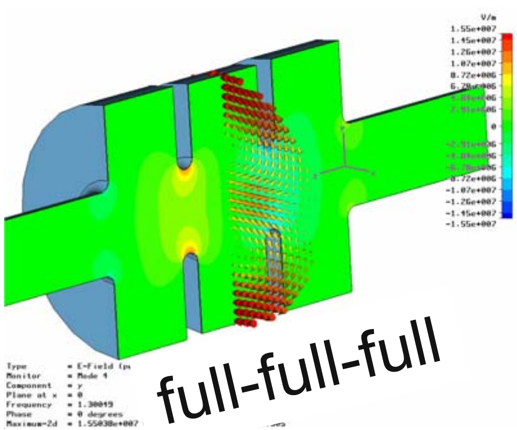
$$E_0 d=\frac{\lambda}{2}(W_0/e)T$$

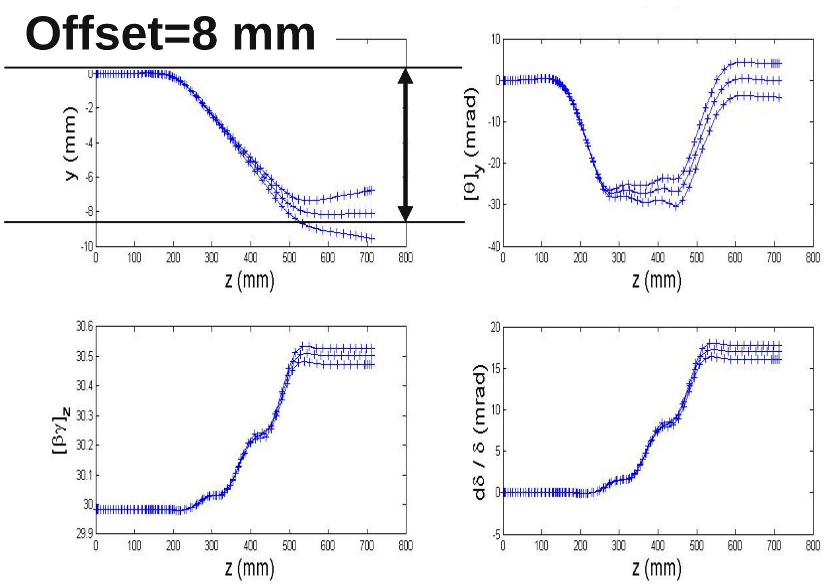
Required field
E_0=60MV/m (1.3 GHz, π-mode)

Deflector Cavity Design

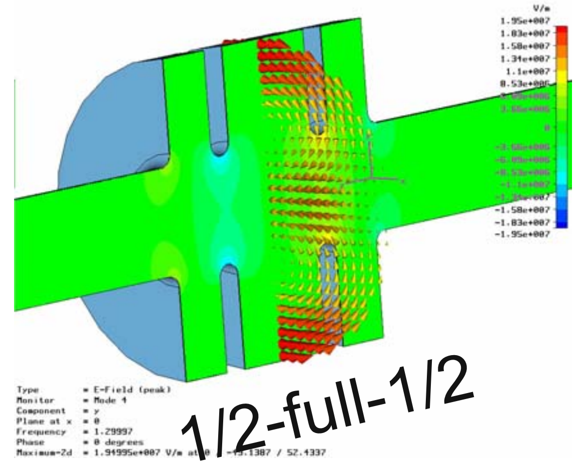
Beam dynamics in real cavity (MWS fields/Matlab tracking)

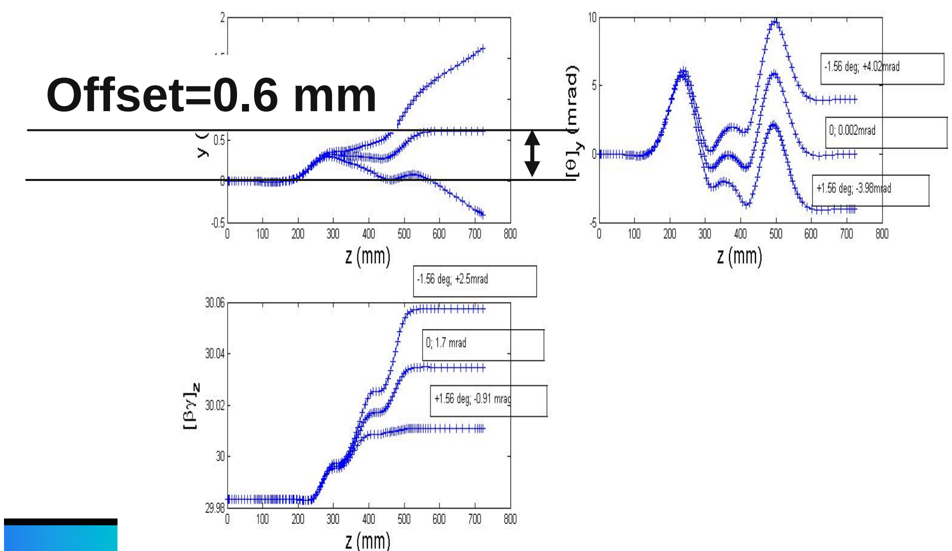
Discovered 'Dogleg Offset'





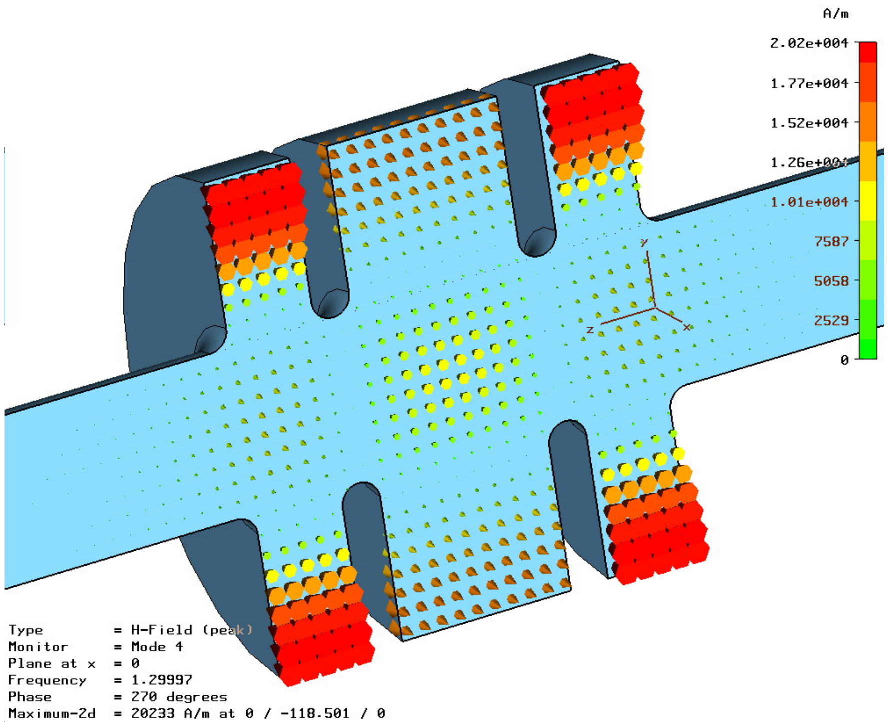
... and found solution

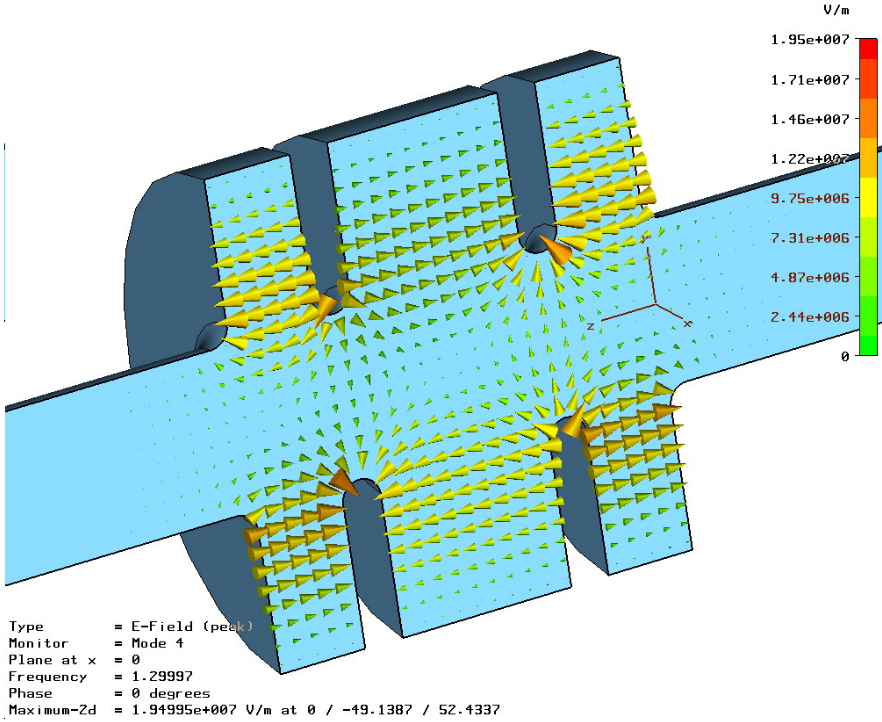




RF design of ½-full-½ deflecting cavity → complete

Engineering Design and Fabrication by Tsinghua Univ.





MWS sims are normalized to U=1J, P=0.51 MW

•max E-field is on the iris ~20MV/m

•max H-field ~20,000 A/m at the outer wall of the half cell.

increase P=2.44 MW

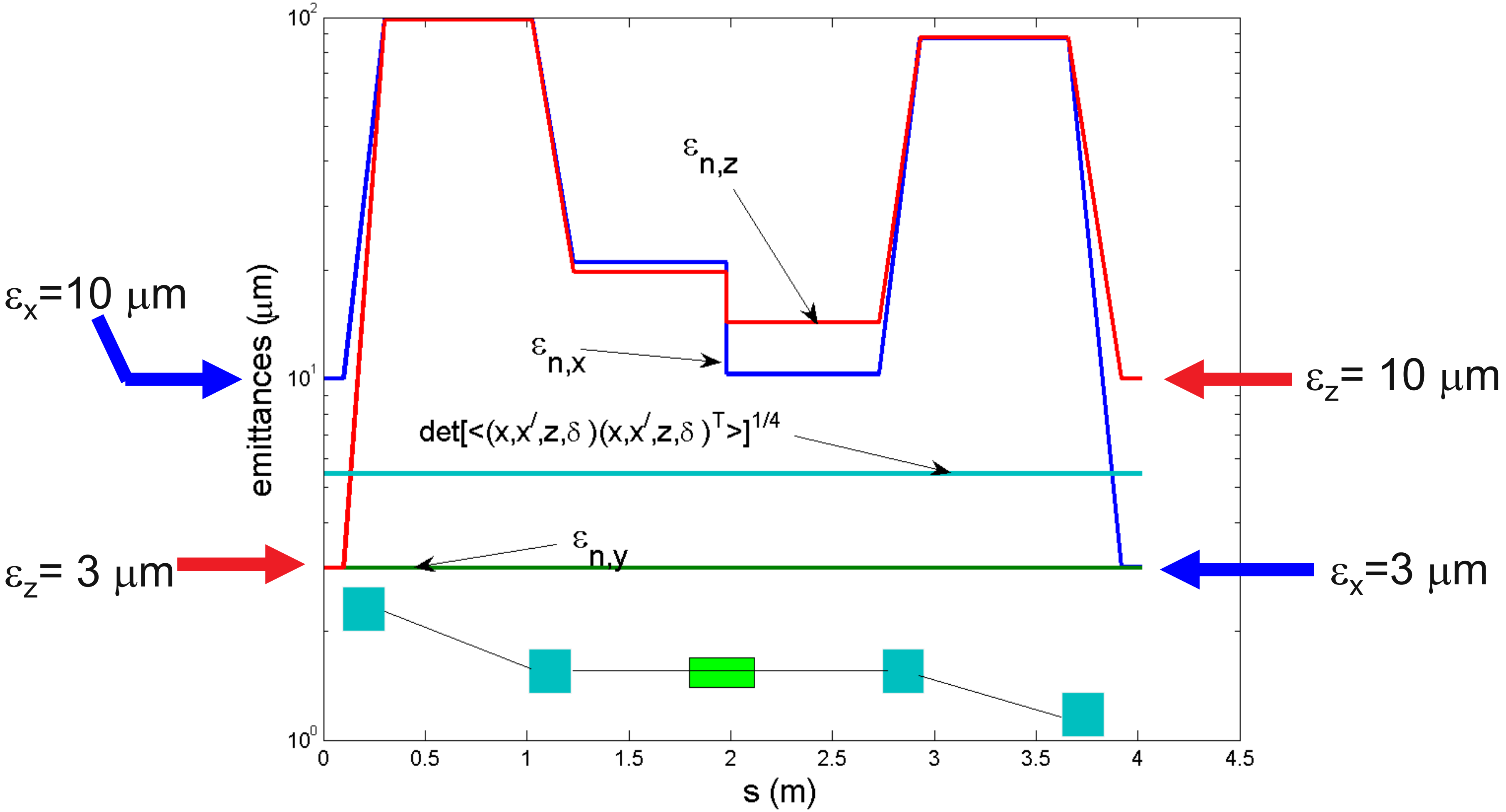
•max E-field is on the iris ~44MV/m

•max H-field ~44,000 A/m at the outer wall of the half cell.

•Average Power= 2.44 MW * 6 usec * 5 Hz = 73 watts

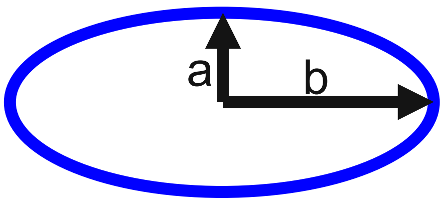
E-X beam dynamics simulations

Thick lens simulations done, collective effects next.

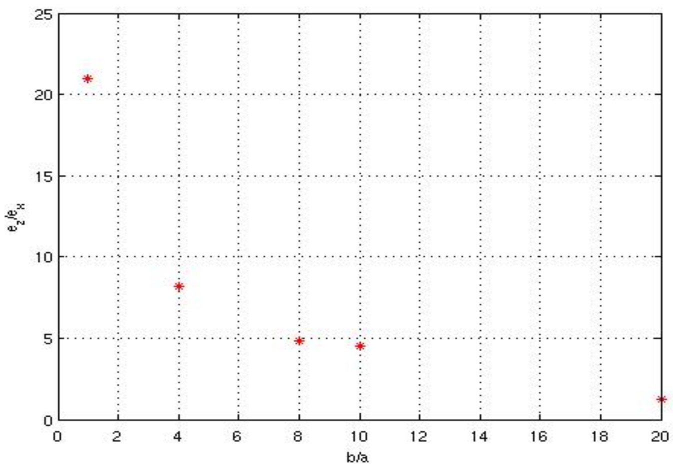


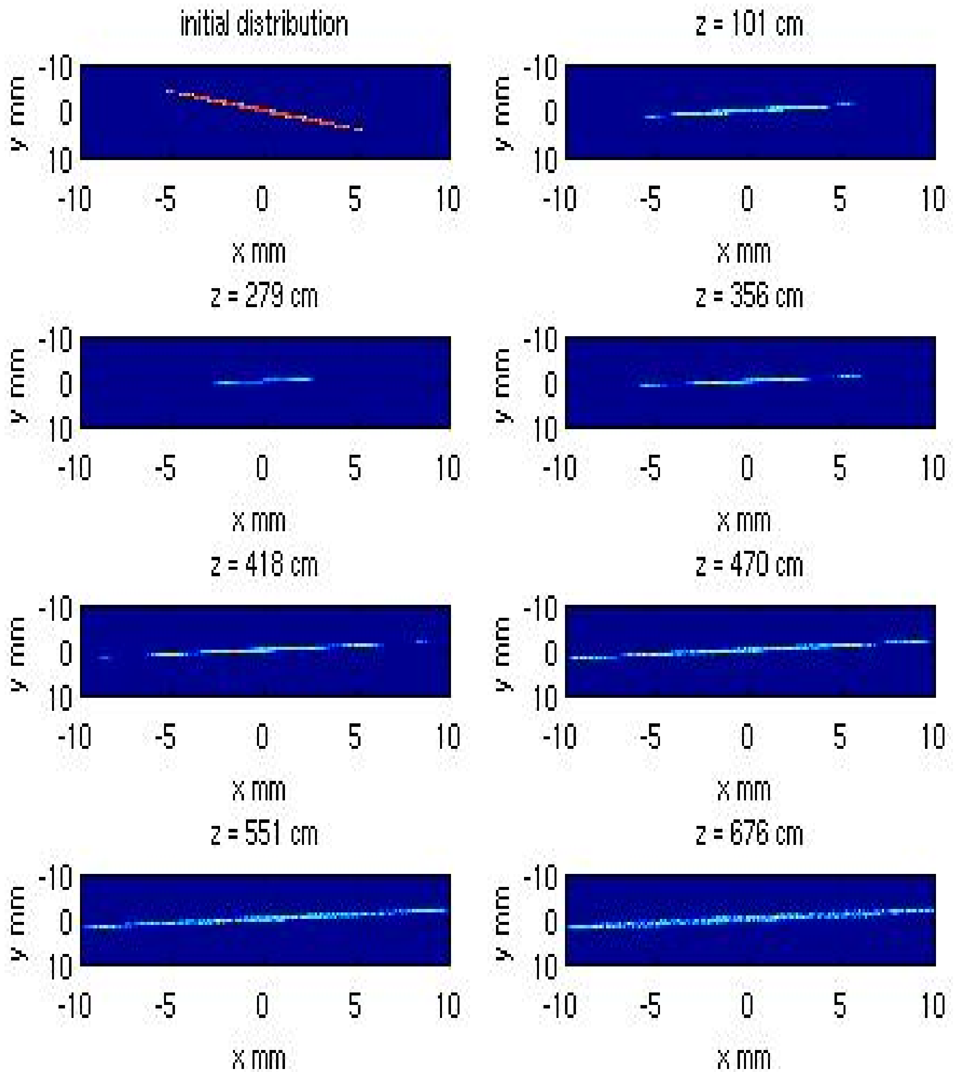
Flat beam production

RF photoinjector laser-based scheme



- Elliptical laser distribution
- Target ε_N is (**10,3,3**) μm





<u>Simulation parameters:</u>

Ez=80MV/m, gun(ϕ)=54^0, a_{rms}=0.25 mm.

Beam Physics Studies at the AWA facility
Summary

- **RF Photoinjector Beam Physics**
  - Transverse Emittance ~ 5 μm @ 1nC → Path to 1 μm is visible
  - Bunch Length σ_z ~2 mm @ 70 nC → I_{pk} = 10 kAmps
  - Use optimized parameters, Measure 4D ε_N at Q = 1 nC in Winter 07
  - Continue parametric study of AWA beam (ε_N at high Q, high Energy)
  - Longitudinal Phase Space Measurement Fall 07
- **Advanced Diagnostic Development**
  - ODR-DFR Interferometer expt't scheduled for Spring 07
  - EOS: perform simulated-beam experiment Spring 07
- **Emittance Exchange Experiment**
  - Cavity design complete
  - First pass beamline simulation complete
  - Demonstrate laser-based flat beam generation Summer 07
  - Diagnostic development and acquiring hardware Summer-Fall 07
  - Commission TOF diagnostics
  - Receive cavity from Tsinghua Spring 08